

Final Report for Grant NCC3-798:
Modeling Nonlinear Acoustic Standing Waves
in Resonators: Theory and Experiments

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1 Participants

1.1 Group at Illinois Institute of Technology

1.1.1 PI: Dr. Ganesh Raman

Dr. Raman is an Associate Professor in the Mechanical, Materials and Aerospace Engineering Department at Illinois Institute of Technology. Dr. Raman supervised the experimental part of the project and coordinated the IIT effort.

1.1.2 co-PI: Dr. Xiaofan Li

Dr. Li is an Assistant Professor at Department of Applied Mathematics at Illinois Institute of Technology. Dr. Li contributed to the theoretical part of the project. He has developed models to account for various configurations of the system, designed the numerical algorithms to solve the boundary value problem of the Ordinary Differential Equations and to find optimal resonator shapes.

1.1.3 Joshua Finkbeiner

Mr. Finkbeiner has been a graduate student during the grant period and obtained his Master's degree in the spring of 2003 working with Dr. Ganesh Raman. His Master's thesis focuses on nonlinear acoustic standing waves in oscillating closed containers. [2] He has worked on both the experimental and theoretical parts of the research. Most of his work has been written in his Master's thesis.

1.2 Partners

The original idea of using the pressure property in a resonator to construct an acoustic non-contact seal for turbine engines belongs to Dr. Bruce Steinetz of NASA-Glenn. During the grant period, he and Dr. Christopher Daniels of the Ohio Aerospace Institute have provided insights on various aspects of the project along with experimental data from the NASA Glenn effort. We have had meetings at IIT and NASA Glenn and teleconferences to discuss the research, including progress, difficulties, and future tasks.

2 Summary of Activities and Findings

2.1 Objective

The overall goal of the cooperative research with NASA Glenn is to fundamentally understand, computationally model, and experimentally validate non-linear acoustic waves in enclosures with the ultimate goal of developing a non-contact acoustic seal. The longer term goal is to transition the Glenn acoustic seal innovation to a prototype sealing device. Lucas and coworkers are credited with pioneering work in Resonant Macrosonic Synthesis (RMS).

Several Patents and publications (Lucas and Van Doren (1996), Lawrenson et al. (1998) [3], and Ilinskii et al. (1998) [1]) by this group have successfully illustrated the concept of Resonant Macrosonic Synthesis. To utilize this concept in practical application one needs to have an understanding of the details of the phenomenon and a predictive tool that can examine the waveforms produced within resonators of complex shapes. With appropriately shaped resonators one can produce un-shocked waveforms of high amplitude that would result in very high pressures in certain regions. Our goal is to control the waveforms and exploit the high pressures to produce an acoustic seal. Note that shock formation critically limits peak-to-peak pressure amplitudes and also causes excessive energy dissipation. Proper shaping of the resonator is thus critical to the use of this innovation.

2.2 Research and Education Activities

1. We developed software to compute the pressure waveforms inside a closed resonator based on the pseudo-one-dimensional model of Ilinskii et al. (1998). We also verified the correctness of the software by comparing the numerical results with those in [1].
2. We derived the governing equations for an oscillating resonator that includes a center shaft, obtained the numerical results for resonators with center-shaft. We also carefully studied the effect of the center-shaft on the acoustic field in the resonator.
3. We designed an experimental set-up that provided results on the RMS phenomenon.
4. We developed a numerical tool that handles cases where shock or hysteresis occurs. The numerical tool was implemented such that it automatically computes the pressure waveform at different frequencies and finds the gas resonant frequency.
5. We derived an analytical model for nonlinear standing wave in an axisymmetric resonator that incorporated a shaft along the axis of symmetry; examined the effects of cylindrical and tapered shafts on Resonant Macrosonic Synthesis; constructed a numerical tool that optimizes a conical resonator shape for seal technology; implemented a version

of the optimizing numerical tool: found the optimal conical shape that maximizes the DC pressure at the narrow end with fixed Ω .

6. We built a numerical tool that does Numerical Optimization, integrated with an automation tool; performed two-parameter optimizations on conical shapes and horncones and considered three-parameter optimization.
7. We developed and implemented a reliable software tool that can find locally optimized and globally optimized resonator shapes.
8. We considered the effect of the size of resonator, the potential weight or size problems and the feasibility of some optimized resonators.
9. Experimental investigation of the acoustics was conducted. Five resonator shapes were tested at varying degrees of input power and at different frequencies. The working fluid in these resonators was laboratory air.
10. The numerical results from the software developed were compared with those from the experimental results. The numerical model used the same five resonator shapes that used in the experimental investigation.
11. We investigated the numerical viscosity in the theoretical model to match with that from the experimental results.

2.3 Findings Resulting from These Activities

2.3.1 Experimental Studies

Two experimental investigations were constructed and used to investigate nonlinearities in acoustic waves. The first, assembled at IIT of lightweight, low-cost materials, provided a view of general trends in the acoustics. However, specific comparisons between cases were difficult due to the shapes of the acceleration waves which were in turn a result of the non-rigidity of the materials used. While nonlinearities were observed in the dynamic pressures in the resonators, much of the energy that could have been provided to the acoustics in the resonator was lost through the structural dynamics. This problem aside, the IIT nonlinear acoustic test facility successfully generated

nonlinear acoustic standing waves in three different resonators. The cylinder resonator was found to agree on a qualitative basis with tests from the literature in that waveform steepening and low levels of dynamic pressure amplitude were observed.

The IIT experiment also found valuable results by testing cone and horn-cone designs. The two resonators demonstrated that nonlinear acoustic shock generation could be avoided by shaping the resonator cross section. The resonators were observed to inhibit the transfer of energy to the higher dynamic pressure harmonics, concentrating nearly all of the energy into the first and second harmonics. Without the higher harmonics, the dynamic pressures could not generate acoustic shocks.

The GRC experiments extended the work at IIT by using a more capable experimental setup. Even though more power was available to the experiments and the resonators attached to the test section, the GRC cone and horn-cone resonator shapes were observed to concentrate the majority of the dynamic pressure energy in the lowest harmonics. Where the IIT resonators demonstrated this phenomenon at low power levels, the GRC resonators demonstrated the same concept at higher powers.

For further details of the findings in this subsection, the reader is referred to the Master's Thesis of Joshua Finkbeiner, see [2].

2.3.2 Findings from Direct Comparison between the Numerical and the Experimental Results

Beyond verifying the general trends observed in the experiments, the numerical computational models also helped to demonstrate that the experimental results in all but the cylinder resonator were generated solely by the fundamental acceleration harmonic. Dissonant resonators produced pressure waveforms of negligible amplitude when excited with acceleration waveforms containing only higher harmonic components. At the same time, the dynamic pressure waveforms generated with acceleration waveforms built from a combination of acceleration harmonics behaved nearly identically to waveforms generated with accelerations constructed from a pure fundamental harmonic.

The computational model was used to directly simulate the experiments performed during this study. The viscosity parameter G was measured by comparing the experimental dynamic pressure levels in the frequency sweep to those computed by the model. While the various matching viscosity parameters did not fall in perfect agreement with each other, one value for G

was more common than the others. In addition, the results from the GRC resonators were considered to be more valid than the IIT resonators due to their more rigid construction.

The computational model was unable to simulate the results accurately for the cylinder resonator. While the model predicted qualitative behavior such as waveform steepening and weak acoustic shock formation, the amplitudes of the waves generated by the computational model were substantially higher than those measured in the experiment. In the shaped resonator designs, however, the computational model worked well, particularly in the GRC resonator designs where the structure was more rigid. With the exception of a couple cases, the value of G tended to agree best with the literature when the acceleration signal was referenced at the wide end of the resonator. The GRC cone and horn-cone resonators both matched a viscosity parameter value of $G = 0.01$ when no shaft was included in the resonators. The inclusion of the shaft complicated the comparison for the cone resonator, but the matching value of G in the horn-cone resonator did not change with the inclusion of the shaft. Experimental data also found the horn-cone resonator to have the highest level of rigidity of any of the tested resonators, so the results from the horn-cone are believed to be the most accurate. Therefore, the assumptions in the literature are supported by this study which matched a viscosity parameter value of $G = 0.01$ to one significant figure. More accurate experiments with more rigid structures are required to gain additional significant digits in the value of G .

The details of the findings in this subsection can be found in the Master's Thesis of Joshua Finkbeiner, see [2].

2.3.3 Optimal Resonator Shapes

The resonant frequencies and the nonlinear standing waveform in an acoustical resonator strongly depend on the resonator geometry. We investigated the problem to maximize the ratio of maximum to minimum gas pressure at an end of an oscillating resonator by optimizing the cavity contour. A quasi-Newton type scheme is used to find optimized axisymmetric resonator shapes to achieve the maximum pressure compression ratio. The acoustical field is solved using a one-dimensional model, and the resonance frequency shift and hysteresis effects are obtained through an automation scheme based on continuation methods. Results are obtained from optimizing cone, horn-cone, and cosine resonator geometries with a significant performance improvement

found in the optimized shapes over others previously published. Different optimized shapes are found when starting with different initial guesses indicating multiple local extrema. The numerical model is verified by comparing with the experimental results of a horn-cone shaped resonator.

A paper has been written on the subject and is submitted to the journal *J. Acoust. Soc. Am.* For details, refer to Appendix A. In the paper, a local optimization scheme is presented for finding the resonator shapes that maximize the pressure compression ratio at one end of an oscillating acoustic resonator. The optimal dimensions are reported for cone, horncone, and cosine shaped resonators. For each type of resonator, a smaller narrow end is found to give a larger pressure peak-to-peak ratio. This finding suggests that the number of shape parameters in an optimization can be reduced by setting the dimension of the narrow end fixed at a value as small as possible. For the types of horncone and cosine shapes, there are many different designs that achieve local extrema. Using different initial guesses for the optimal design, the results show that as much as 196% improvement on the compression ratio can be achieved with a fixed level of input power. For the shapes considered herein, the horncone shape is found to generate the highest compression ratio. Searching strategies for globally optimal shapes are under investigation.

2.3.4 The Effect of the Center Blockage

The effect of including an axisymmetric blockage at the center of the resonators are investigated both experimental and numerically. The inclusion of a shaft in the resonator does not prevent the formation of high amplitude acoustics. The primary effect of a central shaft blockage is that it increases the resonant frequency for a given resonator, although efficiency changes in the resonator also occur via the inclusion of this structure. Some of the shaft cases generates higher pressures than the same resonator without a shaft, however, this is apparently due to an increase in the forcing function applied to the resonator rather than a suppression of the energy transfer mechanisms in the dynamic pressure.

The details of the findings in this subsection can be found in the Master's Thesis of Joshua Finkbeiner, see [2] and the AIAA paper, see Appendix B.

3 Publications and Presentations

1. C. Daniels, J. Finkbeiner, B. Steinetz, X. Li, & G. Raman, *Determination of dimensionless attenuation coefficient in shaped resonators*, presentation 4aPAa3, *145th Meeting of the Acoustical Society of America*, May 2003, Nashville, TN.
2. C. Daniels, J. Finkbeiner, B. Steinetz, X. Li, & G. Raman *Nonlinear oscillations and flow of gas within closed and open conical resonators*, *AIAA Paper No. 2004-0677*, *42nd AIAA Aerospace Sciences Meeting* Reno, Nevada (2004).
3. J. Finkbeiner, *Nonlinear acoustic standing waves in oscillating closed containers*, Master's Thesis, Illinois Institute of Technology, May 2003.
4. J. Finkbeiner, X. Li, C. Daniels, G. Raman, & B. Steinetz, *Effect of forcing on nonlinear acoustic standing waves*, *145th Meeting of the Acoustical Society of America*, May 2003, Nashville, TN.
5. X. Li, J. Finkbeiner, G. Raman, Christopher Daniels, & Bruce Steinetz, *Nonlinear resonant oscillations of gas in optimized acoustical resonators and the effect of central blockage*, *AIAA Paper No. 2003-0368*, *41st AIAA Aerospace Sciences Meeting and Exhibit* (2003).
6. X. Li, J. Finkbeiner, G. Raman, Christopher Daniels, & Bruce Steinetz, *Optimized shapes of oscillating resonators for generating high-amplitude pressure waves*, submitted to *J. Acoust. Soc. Am.*, MS #03-00414.